...rements of the Dynamic Complex ...g's and Shear Moduli of ...orotrifluoroethylene (Kel-F®) ...ng a Resonant Bar Technique

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PREFACE

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The material Kel-F® is a candidate for use as a mechanical transducer in applications requiring small volume, lightweight sensors. However, there is concern that the temperature dependence of its elastic moduli will result in an unacceptable temperature-dependent sensitivity in some configurations.

In this investigation, a cylindrical bar of Kel-F® was selectively excited in its lowest flexural, torsional, and longitudinal modes in order to determine the material elastic properties and to make an estimate of their temperature dependence. A "free-free" bar was excited electrodynamically and from these resonant modes both the Young's and shear elastic moduli were determined. The complex modulus can be found by measuring the quality factor (Q) for each resonant mode. It was concluded that from 0° to 24° C, the Young's modulus varied less than 1.6 dB and the shear modulus less than 2.0 dB.

The measurements were taken by Code 421 in the materials laboratory at the New London Detachment of the Naval Undersea Warfare Center, Division Newport.

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MEASUREMENTS OF THE DYNAMIC COMPLEX YOUNG'S AND SHEAR MODULI OF CHLOROTRIFLUOROETHYLENE (KEL-F®) USING A RESONANT BAR TECHNIQUE

INTRODUCTION

Chlorotrifluoroethylene (CTFE Kel-F®) is a candidate material for acoustic sensors employing fiber optic interferometry and polyvinylidene fluoride (PVDF) piezoelectric-based detection. The motivation in investigating CTFE for underwater acoustics applications is its relatively low acoustic wave speed as compared with that of the surrounding medium (sea water) and alternative transducer materials (e.g., polycarbonate, metals). This feature may be of practical and operational importance in the actual implementation of a sonar array. CTFE also appears to offer a low elastic modulus that will result in high acoustic sensitivity, which is proportional to the strain per unit pressure generated in the transducer in both fiber optic interferometry and PVDF-based detection. A summary of typical properties of CTFE plastics is included in appendix A.

However, the temperature and frequency dependence of the dynamic elastic properties of Kel-F® is not known. While static Young's modulus is typically available, manufacturers do not, in general, provide dynamic mechanical property data for their products. This investigation was initiated to ensure that acoustic sensors made from this material have sensitivities that are sufficiently independent of temperature and frequency.

The report describes the determination of the elastic properties of CTFE Kel-F® by measurement of the resonant modes of a sample bar of the material. The "free-free" bar was selectively excited in its flexural, torsional, and longitudinal vibrational modes with a transducer consisting of coils of magnet wire placed in the magnetic field created by a pair of permanent magnets.[1-3] The resonant modes were electrodynamically detected by use of a second coil located at the opposite end of the sample. The bar was placed on a pair of soft rubber bands so that the ends were free to move. The square of the detected frequency of the flexural and longitudinal resonant modes is proportional to the Young's modulus; the square of the frequency of the torsional modes is proportional to the shear modulus. The quality factor, or Q, of the resonant modes is equal to the ratio of the real to imaginary parts of the complex moduli and the inverse of the characteristic loss tangent. The modulus that is obtained is a dynamic complex modulus at the frequencies corresponding to the fundamental bar resonance and its overtones. Measurements of Kel-F® were taken in Code 4211 at the New London Detachment of the Naval Undersea Warfare Center, Division Newport.

EXCITATION AND DETECTION

The differential Lorentz force, $d\vec{F}$, produced on a segment of wire, $d\vec{l}$, carrying a current, I, in a static magnetic field, $\vec{B}$, is given by

$$d\vec{F} = I\, d\vec{l} \times \vec{B}. \tag{1}$$

As described in the Introduction, longitudinal, torsional, or flexural forces can be generated in order to selectively excite each of the three vibrational modes. The particular mode excited depends on the relative positioning of the wire coils carrying the current, I, and the direction of the magnetic field. Typically, the magnetic field direction and strength created by the pair of permanent magnets, as well as the current driven through the coil of wire, are constant and independent of frequency. When the frequency of the oscillator driving, the wire coil is varied, the bar is excited in its characteristic resonant modes of vibration. The detection of these modes is accomplished by placing the second wire coil at the opposite end of the bar within the magnetic field created by a second pair of permanent magnets. The voltage output of the wire transducer is an electromagnetic force (EMF), which is proportional to the change in magnetic flux linking the coil and is given by

$$V = -\frac{d}{dt}\int_s \vec{B} \cdot \vec{n}\, dA\ . \tag{2}$$

For a small segment of wire moving with velocity $\vec{u}$ in a magnetic field $\vec{B}$, the induced EMF is given by

$$V = \vec{B}\ \vec{l} \times \vec{u}\ . \tag{3}$$

The HP3562 (dynamic signal spectrum analyzer) was used in a swept sine mode in the appropriate frequency range to excite each mode of vibration. The experimental setup is illustrated in figure 1. The resonances were determined from the displayed frequency response and the quality factors from the frequency/damping special cursor feature of the analyzer.

THEORETICAL RESONANCE FREQUENCY

Once the resonances have been determined and the dimensions and density of the bar measured, the appropriate moduli can be calculated from the equations presented in this section. A uniform, cylindrical rod-shaped sample of a homogeneous, isotropic solid having circular cross-sectional diameter, d, and length, L, (which is significantly greater than its diameter) will propagate three independent waves if its wavelengths, λ, are much greater than d.

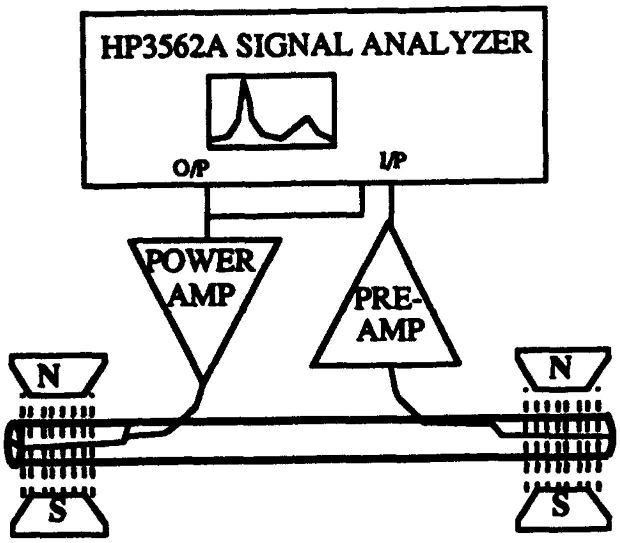

Figure 1. Measurement Setup for the Electrodynamic Excitation and Detection of Modes of a Bar

The displacements associated with the longitudinal and torsional modes satisfy a partial second-order wave equation, and for a free-free boundary condition, the resonances are harmonically related. The Young's modulus can be expressed as

$$E = 4\rho L^2 \left(\frac{f_n}{n}\right)^2 , \tag{4}$$

where n is a positive integer, f_n is the resonance frequency of the nth mode, and ρ is the density of the sample bar. Similarly, the shear modulus can be expressed as

$$G = 4\rho L^2 \left(\frac{f_n}{n}\right)^2 . \tag{5}$$

The measurement of the flexural mode provides a second measure of the Young's modulus, and its fundamental frequency is typically an order of magnitude lower than the longitudinal modes. The flexural waves of the bar obey a fourth-order differential equation, and the flexural wave phase speed is dispersive. The application of "free-free" boundary conditions in this case leads to a series of modes that are overtones but not harmonics. The Young's modulus can be expressed in terms of the flexural modes (where η is equal to 3.011, 5, 7, 9, 11, and so forth) as

$$E = \frac{1024}{\pi^2} \frac{\rho L^4}{d^2} \left(\frac{f_\eta}{\eta^2}\right)^2 . \tag{6}$$

MEASUREMENTS AND RESULTS

The sample bar of Kel-F® had a 1.274-cm diameter, 30.80-cm length, and 2020-Kg/m^3 density. The bar weighed 79.3 gm without the added 1.3-gm mass of two transducer coils and epoxy. The transducer coil length was approximately 2.5 cm. The flexural, torsional, and longitudinal modes were clearly detected from the transducer coil output. Data were obtained at room temperatures of 24° ± 1° C and 0° ± 5° C. The large uncertainty in the low temperature is due to fact that the sample was tested in the open laboratory after it was cooled in and removed from a small environmental chamber. The complex shear and Young's moduli corresponding to these resonances are tabulated in table 1.

Table 1. Summary of the Frequencies of the Modes of Vibration and Corresponding Elastic Moduli of the CTFE Sample Bar

Mode # [n]	Frequency [f_n] (Hz)	Freq/Mode # [f_n/n] (Hz)	Quality Factor [Q]	Modulus
Torsional	T = 24° ± 1° C			(shear modulus)
1	1000	1000	15	0.766 GPa
2	2067	1034	9	0.819 GPa
3	3099	1033	14	0.817 GPa
Torsional	T = 0° ± 5° C			(shear modulus)
1	1127	1127	9	0.97 GPa
2	2308	1154		1.0 GPa
3	3533	1177		1.1 GPa
Longitudinal	T = 0° ± 5° C			(Young's modulus)
1	1766	1766		2.4 GPa
Flexural	T = 24° ± 1° C			(Young's modulus)
$(3.0112)^2$	120	13.2	10	2.0 GPa
$(4.9994)^2$	332	13.3		2.0 GPa
Flexural	T = 0° ± 5° C			(Young's modulus)
$(3.0112)^2$	130	14.6	10	2.4 GPa

CONCLUSIONS

The Young's modulus varies 1.6 dB over the temperature range from +24° C (2.0 GPa) to 0° ± 5° C (2.4 GPa) as obtained from the data of the flexural resonant modes. The Young's modulus was also determined to be 2.4 GPa 0 ± 5° C from the longitudinal modes. The shear modulus varies 2.0 dB over the temperature range from +24° C (0.77 GPa) to 0 ± 5° C (0.97 GPa) as determined from the data of the torsional resonant modes. Frequency response data for the CTFE bar at various temperatures are presented in appendix B of this report. Corrections for transducer mass and stiffness loading were not presented in this analysis. However, these corrections are expected to change the results by less than 5 percent.

The sensitivity of a fiber optic interferometric mandril hydrophone is expected to vary with temperature to the same magnitude as the elastic modulus. This is due to the fact that the sensitivity is proportional to the strain in the mandril and the strain is inversely proportional to the elastic modulus.

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APPENDIX A

CHLOROTRIFLUOROETHYLENE (KEL-F®) MANUFACTURER'S PRODUCT DATA SHEET

KEL-F® CTFE CHLOROTRIFLUOROETHYLENE

Kel-F 81 is the homopolymer of *chlorotrifluoroethylene* (CTFE) manufactured by 3M. This fluoropolymer possesses a number of properties not usually found in other flucropolymer resins. Examples of these properties are optical transparency, high hardness, high compressive strength, and an exceptional resistance to cold flow.

While CTFE does deform slightly under load, it exhibits excellent elastic memory and will recover when the load is removed. As with most thermoplastics, its physical strength will decrease as the temperature increases.

Because it is a highly fluorinated resin, CTFE is non-flammable and relatively unaffected by most corrosive chemicals. CTFE maintains its excellent electrical insulating capability through thermal cycling and high humidity. It has excellent cut-through resistance, remains flexible, and can be bent without cracking at extremely low temperatures.

CTFE offers high optical transmittance, low haze and low gas and moisture vapor transmission. It also exhibits non-wetting and zero moisture absorption. Its dimensional stability is unaffected by high humidity and under prolonged immersion in water.

Summary of typical properties of "Kel-F" 81 Plastic

Property	Typical Values	ASTM Method
Mechanical @ 73°F (23°C)		
Tensile strength @ yield	4600 to 5725 psi (32 to 40 MPa)	D638
@ break	4800 to 5200 psi (33 to 36 MPa)	D638
Elongation @ break	150%	D638
Flexural modulus of elasticity	185x10³ to 255x10³ psi (1280 MPa) to (1750 MPa)	D790
Compressive yield strength @ 0.2% offset	5,500 psi (380 MPa)	D695
Tensile modulus of elasticity	206x10³ psi (1421 MPa)	D638
Flammability		
Oxygen index	100%	D2863
Vertical burn rating	94 VE-O	UL94
Thermal stability		
Zero strength time	200-420 secs	D1430
Useful temperature range	−400 to +400°F (−240 to +204°C)	
Heat distortion temperature under load		
@ 66 psi stress (0.46 MPa)	258°F (126°C)	D648
@ 264 psi stress (1.82 MPa)	167°F (70°C)	
Coefficient of thermal expansion	Below Tg* 4.8×10^{-5} in./in./°F (4.2×10^{-5} cm/cm/°C)	
*Tg (125-140°F) (71-88°C)	Above Tg* 18×10^{-5} in./in./°F (8.8×10^{-5} cm/cm/°C)	
Other properties		
Specific gravity @ 73°F (23°C)	2.10	D792
Water absorption @ 73°F (23°C)	0%	D570
Hardness, Shore D	75-80	D1706
Melting point, Tm	410-420°F (210-215°C)	DTA

APPENDIX B

FREQUENCY RESPONSE DATA FOR THE TORSIONAL, LONGITUDINAL, AND FLEXURAL RESPONSE OF KEL-F® BAR AT VARIOUS TEMPERATURES

GLOSSARY OF NOMENCLATURE

Fh	Frequency harmonic
D	Damping
Ya	Amplitude corresponding to round cursor
x	Frequency corresponding to round cursor

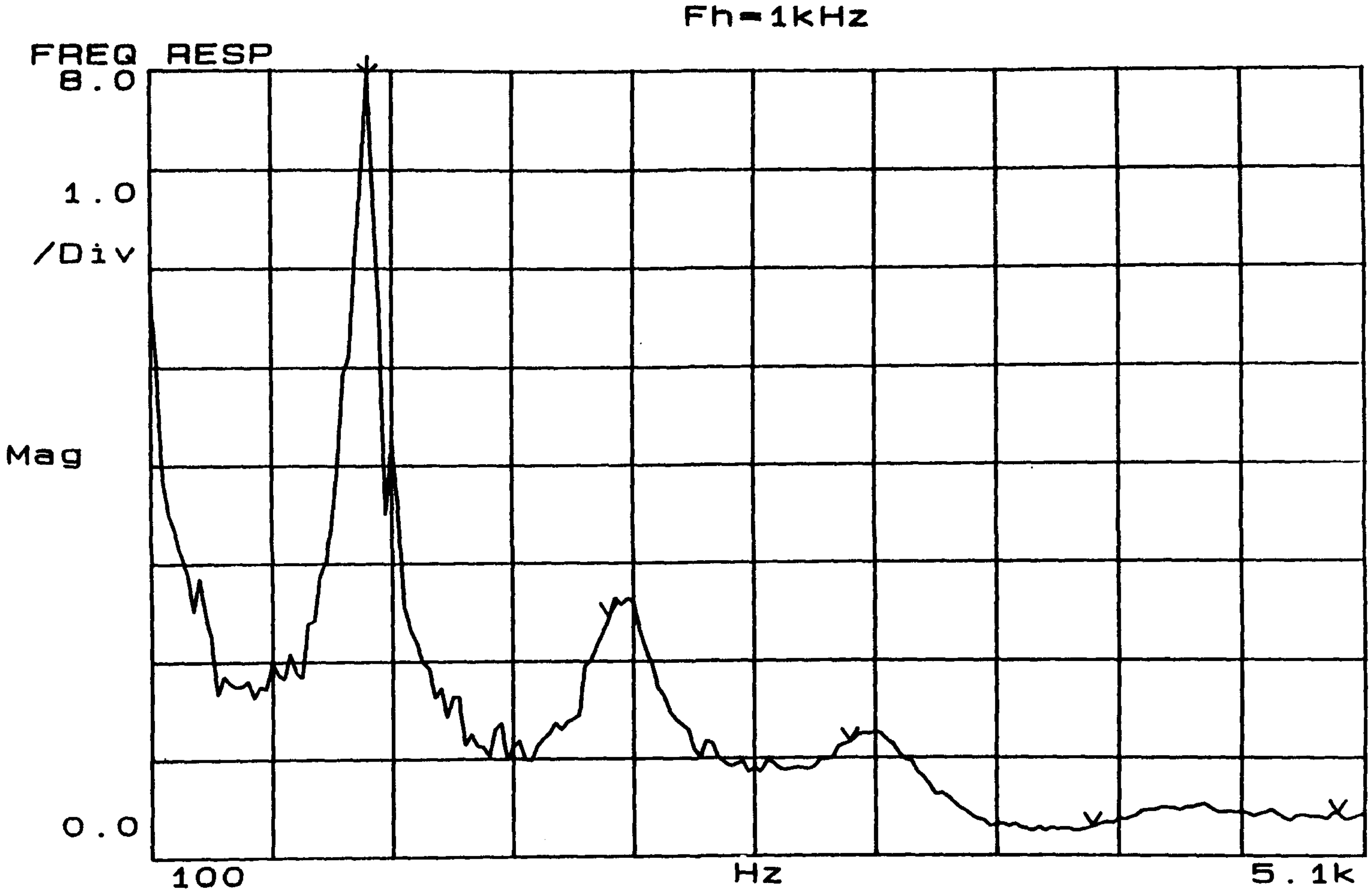

Figure B-1. Torsional Response of Kel-F® Bar at T = 24 ± 1° C

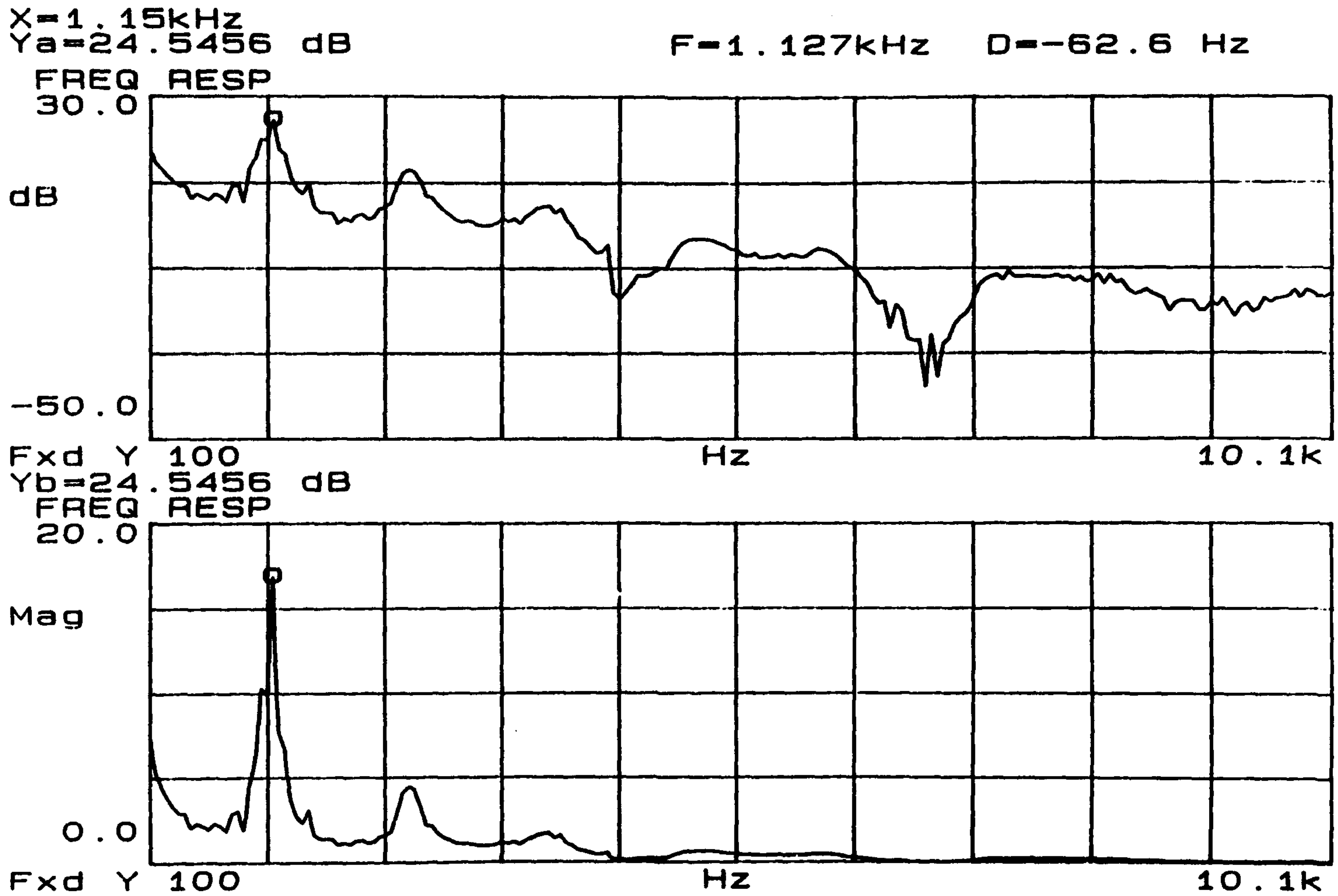

Figure B-2. Torsional Response of Kel-F® Bar at T = 0 ± 5° C

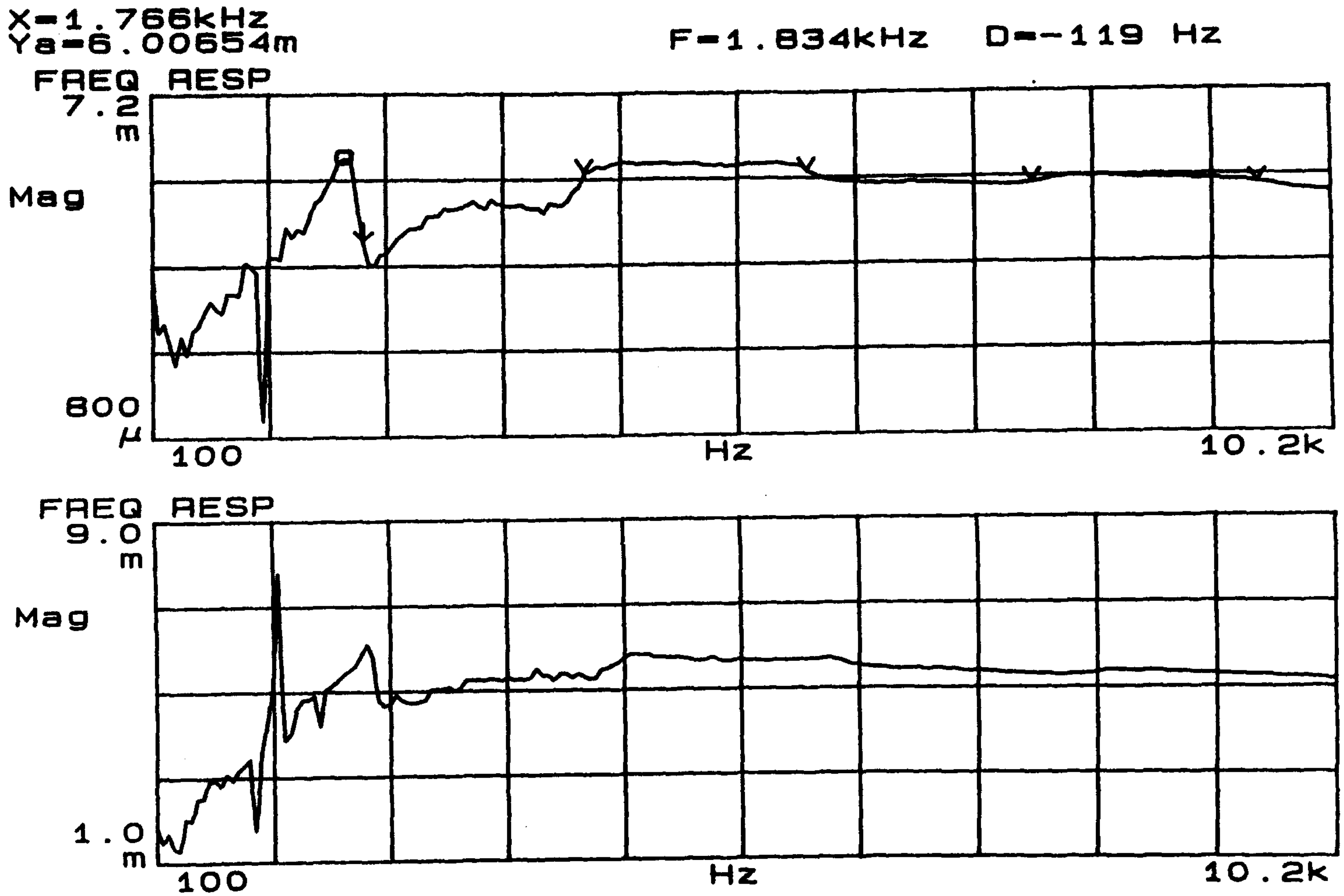

Figure B-3. Longitudinal Response of Kel-F® Bar at T = 0 ± 5° C

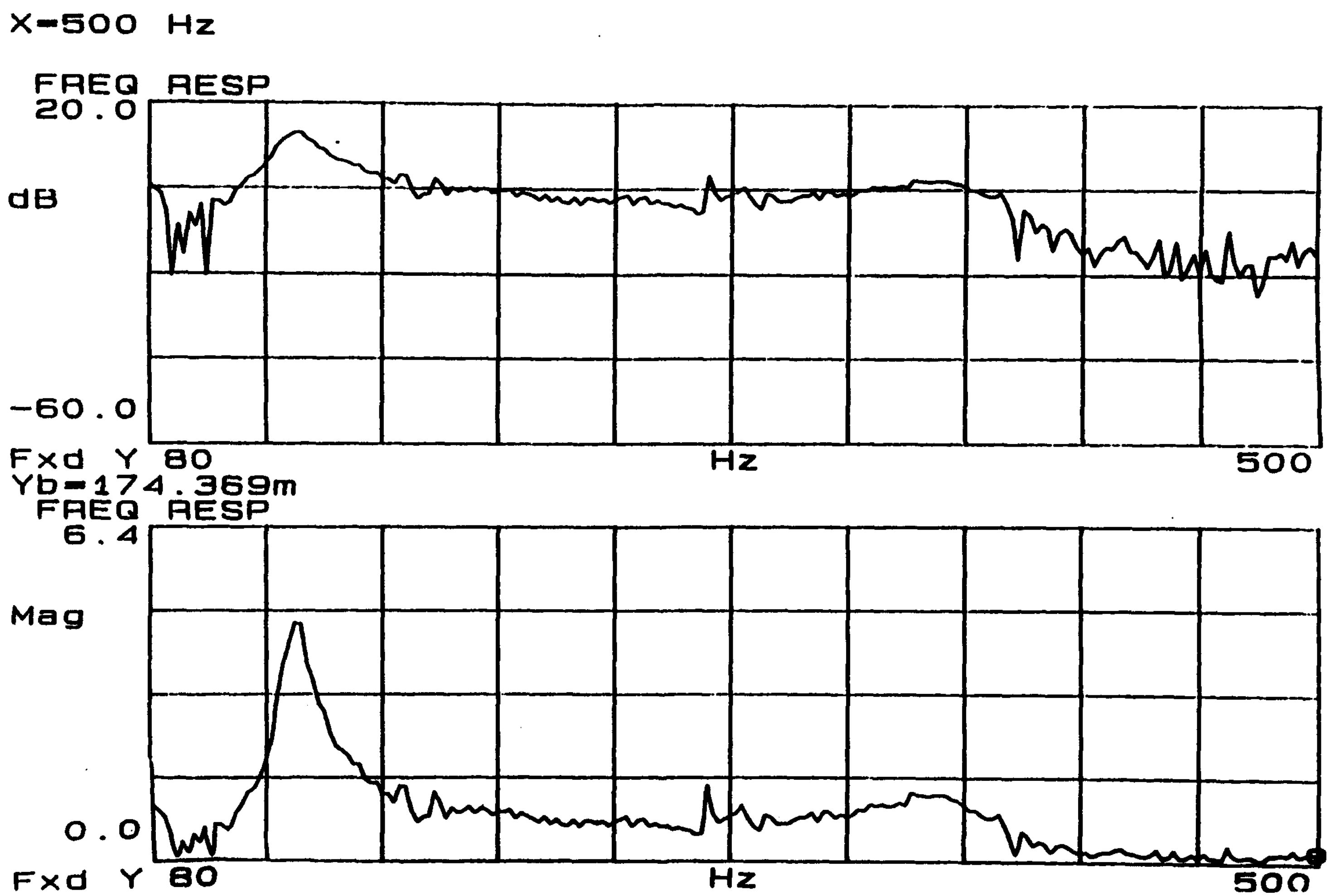

Figure B-4. Flexural Response of Kel-F® Bar at T = 24 ± 1° C

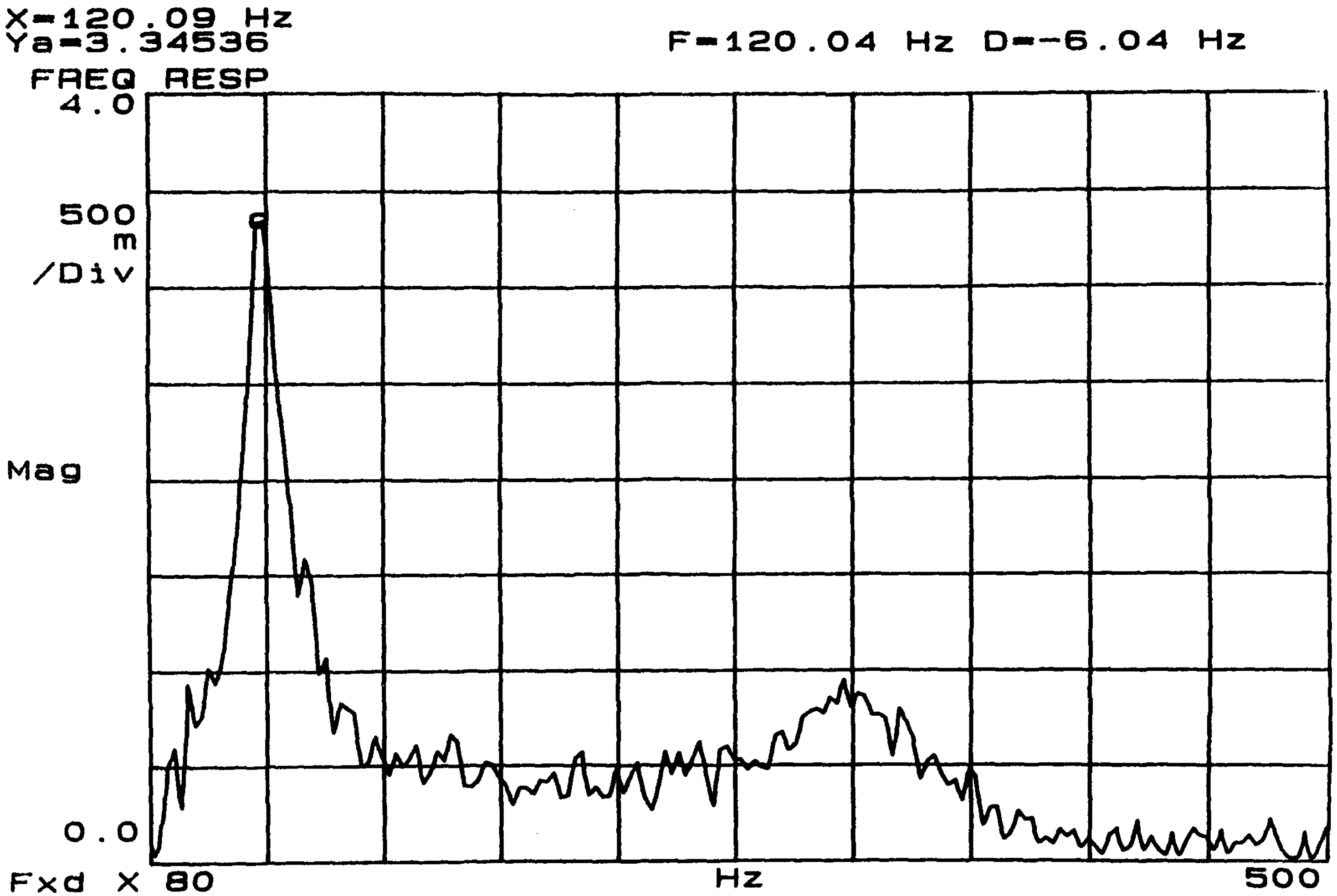

Figure B-5. Flexural Response of Kel-F® Bar at T = 0 ± 5° C

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